A STUDY OF ELEMENT INTERACTION IN THERMOACOUSTIC ENGINES

ANNUAL REPORT

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PHYSICAL ACOUSTICS RESEARCH GROUP
DEPARTMENT OF PHYSICS AND ASTRONOMY

A STUDY OF ELEMENT INTERACTION IN THERMOACOUSTIC ENGINES

ANNUAL REPORT

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Submitted by:
Henry E. Bass, Richard Raspet, James R. Belcher and James Brewster
Physical Acoustics Research Group
Department of Physics and Astronomy
The University of Mississippi
University, Mississippi 38677

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Henry E. Bass, Richard Raspet, James R. Belcher and James Brewster

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Dept. of Physics & Astronomy
University of Mississippi
University, MS 38677

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13. ABSTRACT *(Maximum 200 words)*
Element interaction in a heat driven thermoacoustic refrigerator and high amplitude drive effects on refrigeration are the two lines of investigation being pursued in this project. Energy analysis of a heat driven thermoacoustic refrigerator and high amplitude drive effects are specifically addressed in this report.

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ANNUAL REPORT

BRIEF DESCRIPTION OF PROJECT

The physical understanding of thermoacoustic engines has progressed rapidly in the past five years. The general performance of prime movers and refrigerators is now reasonably well understood and documented. There are, however, notable discrepancies between theory and experiment, especially at large acoustic amplitudes. The discrepancies are typically attributed to non-linear terms not included in the theory. Acoustic streaming is often mentioned as the culprit and this may well be the case. There is evidence, however, that interactions between elements in the engine are at least partially responsible for the differences. This is illustrated, for example, by Swift's observation that the heat exchanger appears to be effective over larger acoustic displacements that simple geometric arguments predict. Additional element interactions will arise when a thermoacoustic prime mover and a refrigerator are placed in the same acoustic resonator. This three year project centers on the studies of different thermoacoustic element geometries.

BRIEF DESCRIPTION OF ACCOMPLISHMENTS

Element interaction in a heat driven thermoacoustic refrigerator and high amplitude drive effects on refrigeration are the two lines of investigation being pursued in this project. James Belcher is investigating element interaction. James Brewster is working on high amplitude drive effects. A detailed description of the work follows.

A. Energy Analysis of a Heat Driven Thermoacoustic Refrigerator

The basic thermoacoustic engine (prime mover) can be separated into five individual sections. These are the resonator, gas, ambient heat exchanger, hot heat exchanger, and the

stack. The addition of another stack and two more heat exchangers into the resonator yields a heat driven thermoacoustic refrigerator.

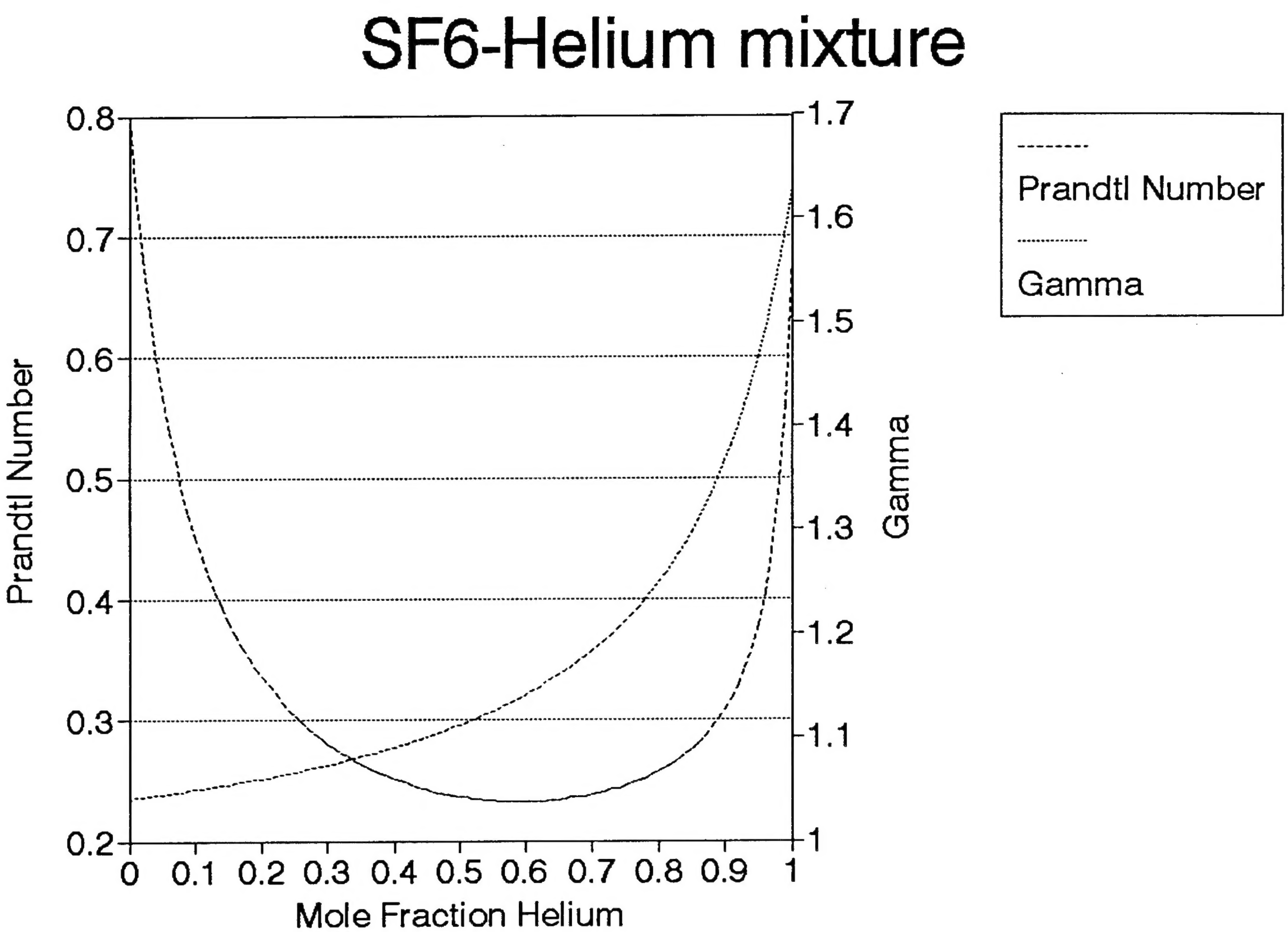
Working Fluid (Gas)

The work produced in a thermoacoustic prime mover is proportional to γ-1, where γ is the ratio of the specific heats, this term is commonly referred to as the work parameter of the fluid. For a monatomic gas, such as helium, γ-1 is approximately 2/3 for a wide range of temperatures. Another important property is the Prandtl number, $\sigma = \nu/\kappa$, where ν is the kinematic viscosity and κ is the thermal conductivity. For a monatomic gas the Prandtl number is 0.7 for a wide range of temperatures.

The ideal working fluid in thermoacoustics would have a large γ and small σ. This would maximize the thermodynamic process on which the prime mover is based to mainly thermal conduction, while the viscous losses would be reduced. Many pure gases meet the condition of high γ, but not small σ, mixtures are the only way to accomplish this. Figure 1 shows the theoretical predictions for mixtures of sulfur-hexafluoride and helium. A mixture consisting of 5% SF_6 and 95% helium decreases σ by 40% while γ decreases by only 10%, numerically this translates to a 15 degree drop in onset temperature of the prime mover.

Heat Exchangers

Heat exchangers are used in thermoacoustics to supply and extract heat at the end of the stack. Their presence is purely dissipative in both viscous and thermal processes. The commonly used heat exchanger consists of parallel fins heated and cooled externally (Fig. 2a). This design relies on heat conduction to supply and extract heat, which is very slow and inefficient. Figure 2b shows the new design for the hot heat exchanger using nichrome wire which supplies heat directly to the end of the stack by convection and conduction through the gas eliminating the need for the fins, thus reducing the viscous and thermal losses inside the heat



SF6-Helium mixture
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Prandtl Number
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
Gamma
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Mole Fraction Helium
Prandtl Number
Gamma

Figure 1

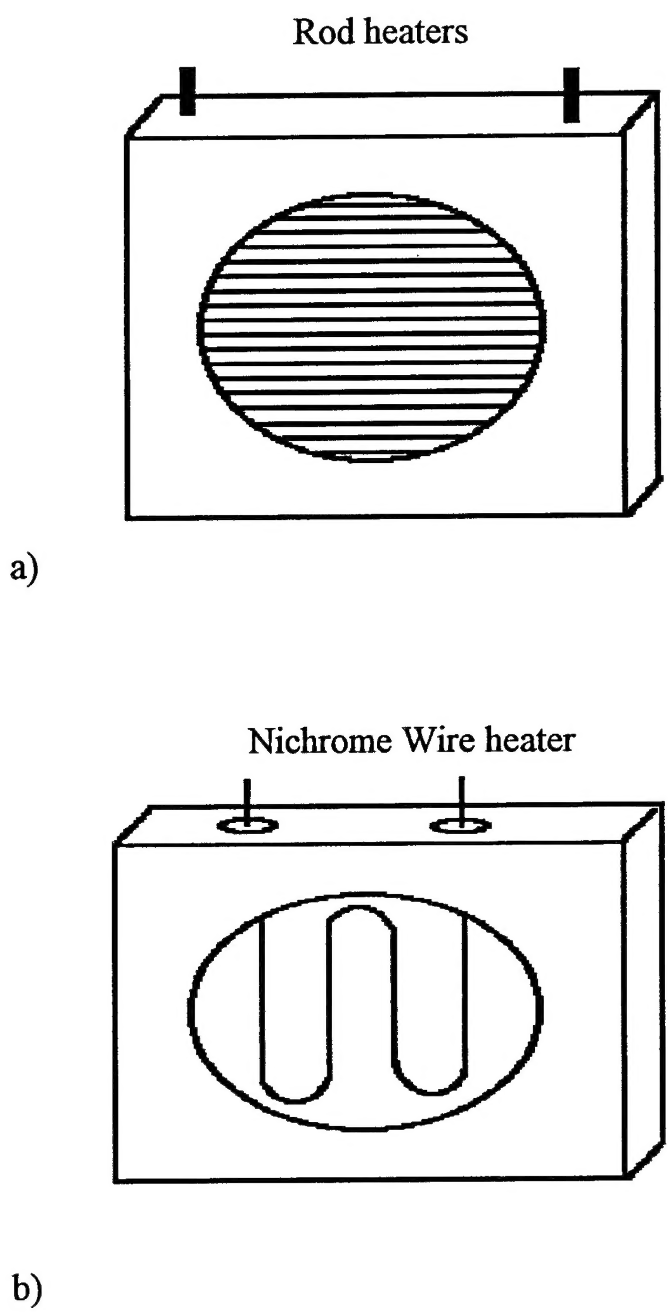


Figure 2

exchangers. In the parallel fin heat exchanger the rod heaters supply 480 watts for 30 minutes to achieve onset, while the nichrome heater supplies 60 watts and onset occurs within the first minute.

Decreasing the length of the heat exchanger is presently under investigation. Preliminary results show that decreasing the length of the hot and cold heat exchangers to 0.32 cm from the present length of 1.8 cm decreases onset temperature by 25 degrees to 120 C.

Stack - Heat Exchanger Interaction

The interaction between stack and hot heat exchanger is very important for low delta T prime movers. Figures 3a and 3b shows the experimental configuration used to illustrate the effects of convection between the two. In Fig. 3a heat is convected away from the stack into the hot end of the resonator. The onset temperature for this configuration is 150 C. In Fig. 3b heat is convected into the stack yielding a lower onset temperature of 145 C.

The hot heat exchanger position relative to the stack is shown in Fig. 4. The hot heat exchanger is displaced away from the stack by small increments to investigate the convective heat transfer. Displacing the hot heat exchanger away from the stack by as little 0.2 cm increases the onset temperature by 40 degrees. This leads us to believe that convective heat transfer is short range. The other striking aspect of this figure is that once the prime mover is oscillating the heat input can be decreased lowering the temperature difference by 20 degrees while still maintaining the oscillations. This has to be associated with the particle displacement being large enough so the gas in the end of the stack, during an acoustic cycle, is in thermal contact with the fins of the heat exchanger. This leads us to believe that decreasing the length of the heat exchangers should increase the performance of a prime mover.

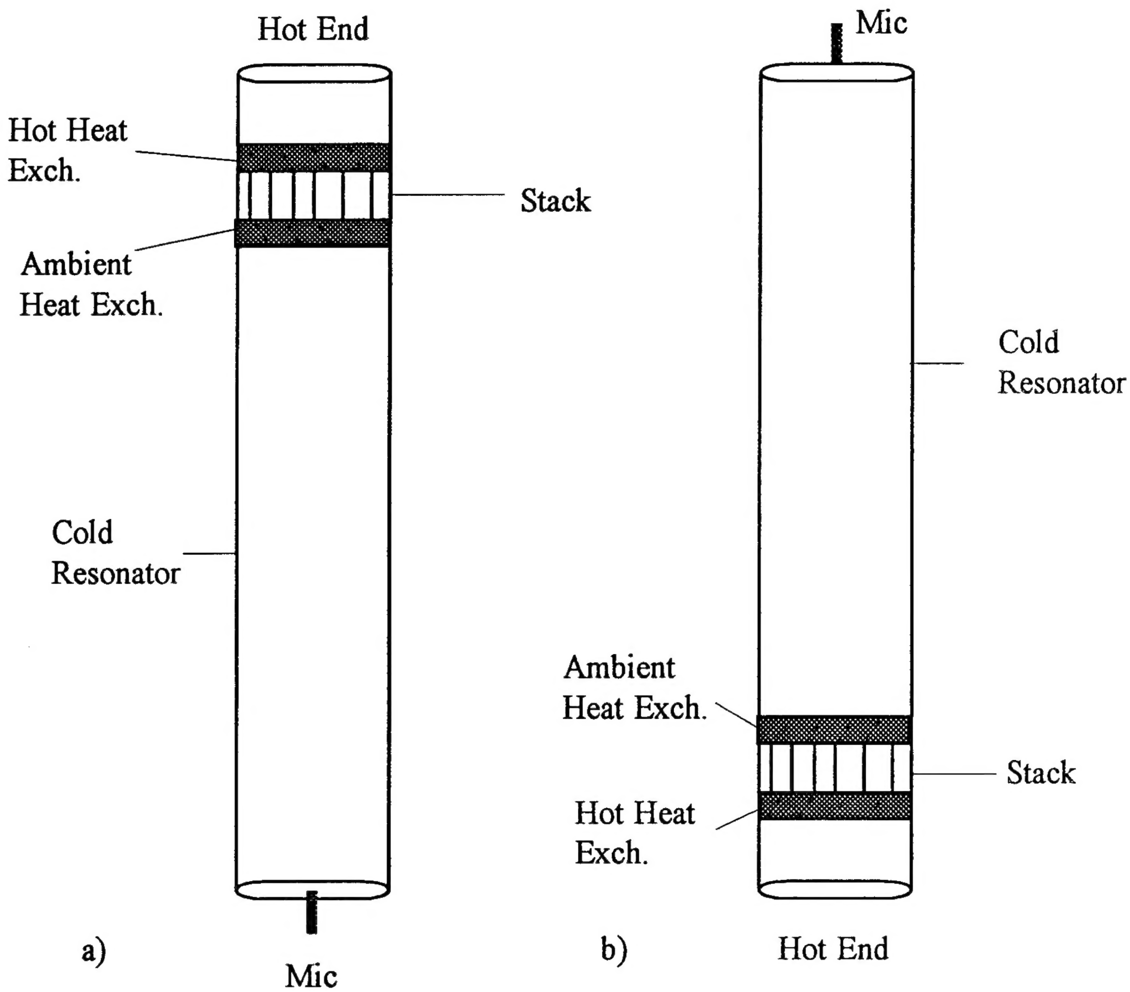
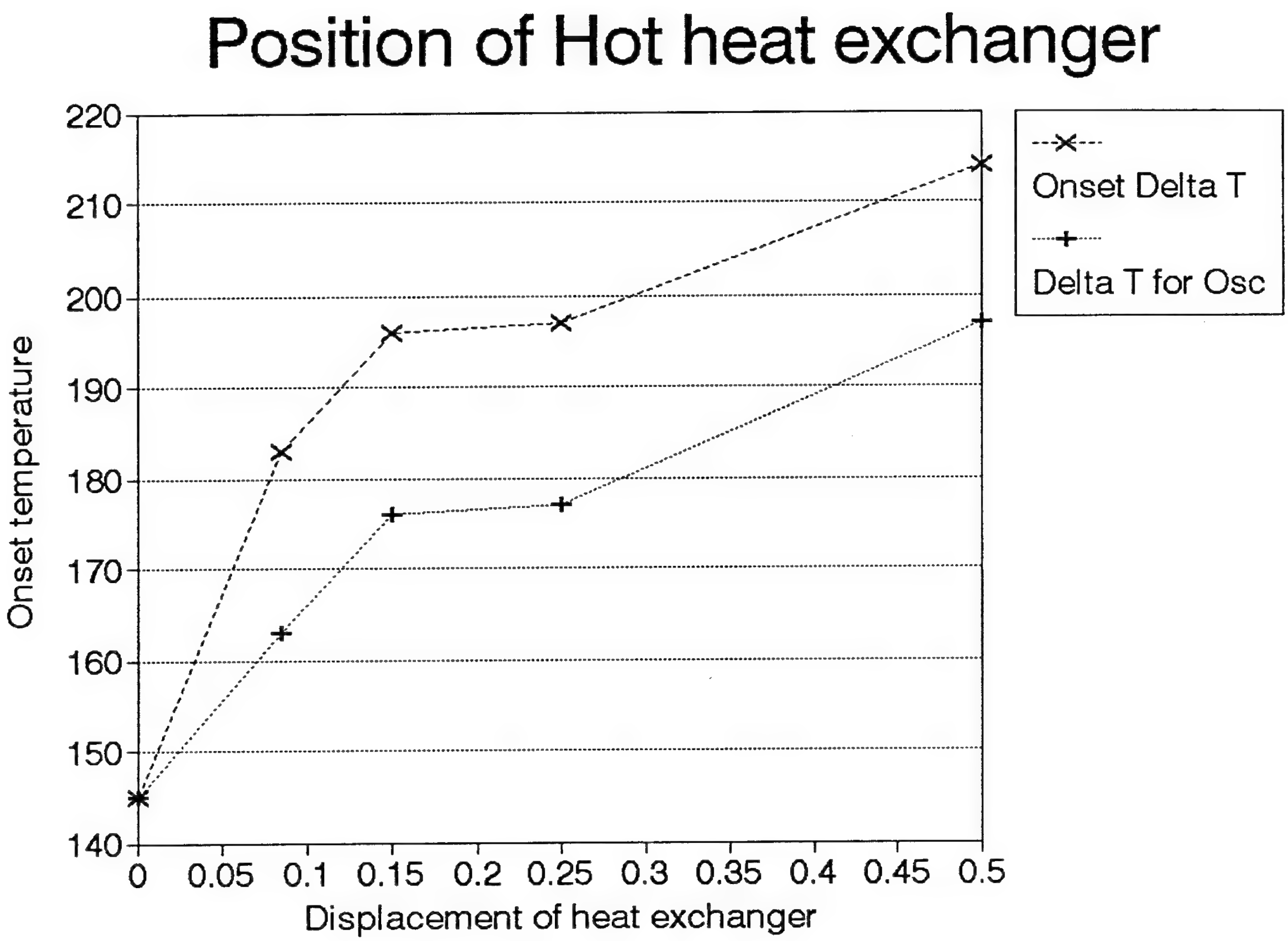

Hot End
Hot Heat Exch.
Stack
Ambient Heat Exch.
Cold Resonator
a)
Mic
Mic
Cold Resonator
Ambient Heat Exch.
Stack
Hot Heat Exch.
b)
Hot End

Figure 3



Position of Hot heat exchanger
220
210
200
190
180
170
160
150
140
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Onset temperature
Displacement of heat exchanger
Onset Delta T
Delta T for Osc

Figure 4

Stack-Stack Interaction

The acoustic power produced in the stack is proportional to the temperature difference across the stack, while the viscous and thermal losses are proportional to the length. The experimental and theoretical results of varying the stack length are shown in Fig. 5. There is good agreement for the short stacks, but losses are over predicted in the longer stacks.

The final objective is to add a heat pump section into the resonator along with the prime mover section to create the heat driven refrigerator (Fig. 6a). The position must be determined experimentally and theoretically. The refrigeration stack was positioned form z = 129 cm to z = 0, where z = 129 corresponds to the configuration shown in Fig. 6b. Moving the heat pump to various position and measuring the temperature necessary for onset of the prime mover is shown in Fig. 6b. The heat pump section was maintained at a constant temperature, therefore the losses were primarily viscous. Figure 6b shows that the minimum delta T occurs when the heat pump section was positioned at the end of the resonator, where the velocity approaches zero.

B. High Amplitude Drive Effects

In all but very few applications, if thermoacoustic refrigerators are to be competitive with existing technologies they must be capable of producing a comparable level of cooling power. If the working fluid is gaseous, the energy density required is such that, at practical ambient pressures, the amplitude of oscillation must be higher than that usually encountered in acoustics. As the relative fluctuation of pressure approaches 10% the assumptions of linear acoustics start to break down. Clearly understanding the departure of the performance of these devices from that predicted by linear theory is of great importance to the design of future thermoacoustic devices.

The finite amplitude phenomena likely to affect thermoacoustic refrigeration are the generation of higher harmonics and the presence of DC gas flows or streaming. There also may be unidentified manifestations of non-linearity that are unique to thermoacoustics. In order to evaluate these effects a resonance tube driven by a high amplitude driver into which can be

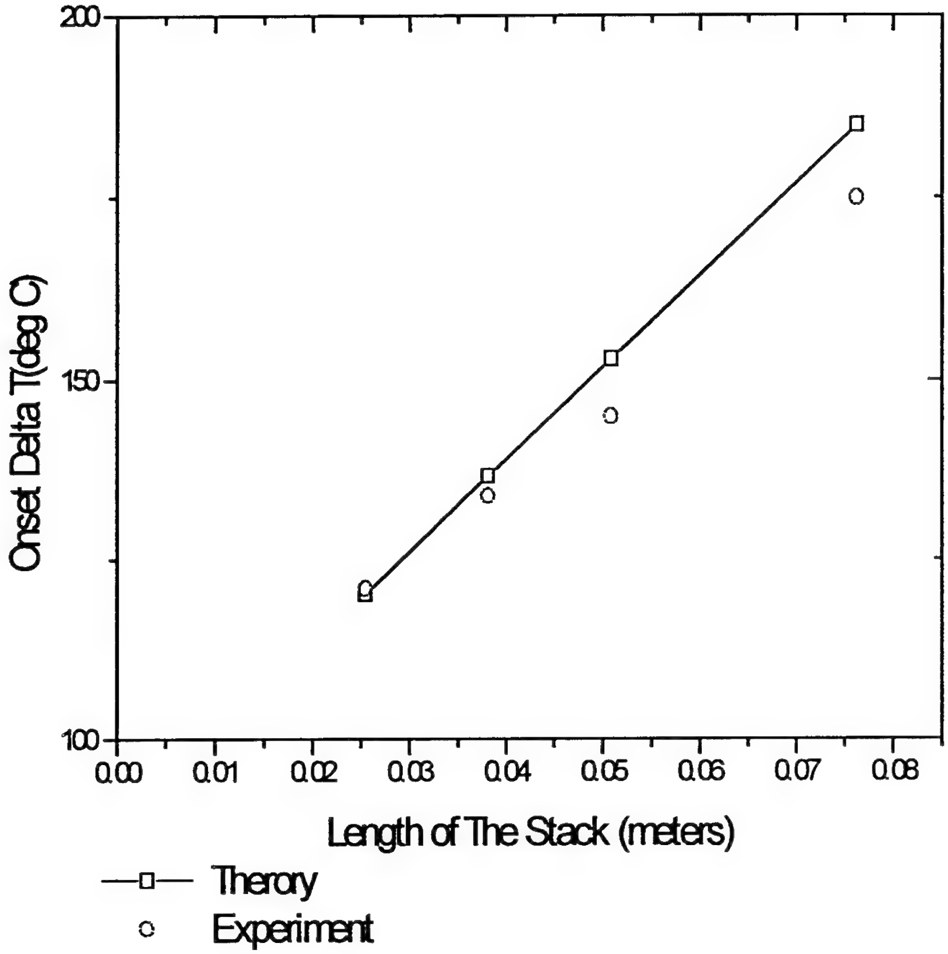

200
150
100
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Onset Delta T(deg C)
Length of The Stack (meters)
Therory
Experiment

Figure 5

a)

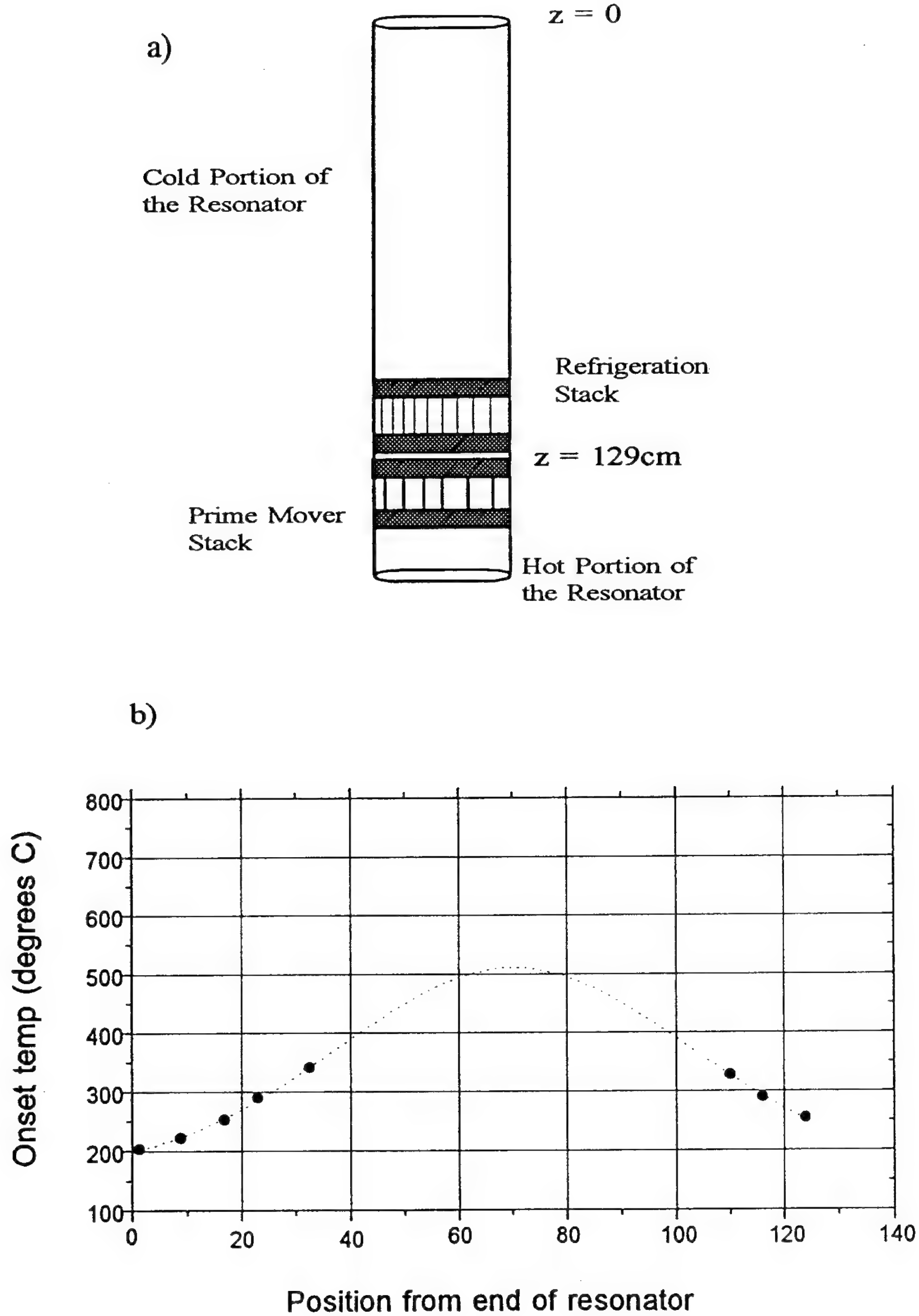

z = 0
Cold Portion of the Resonator
Refrigeration Stack
z = 129cm
Prime Mover Stack
Hot Portion of the Resonator
b)
Onset temp (degrees C)
800
700
600
500
400
300
200
100
0
20
40
60
80
100
120
140
Position from end of resonator

Figure 6

placed elements of a thermoacoustic refrigerator has been built. The design is modular allowing the experiment to be run with the resonator either empty or containing various combinations of stack and heat exchanger elements.

All the experiments performed to date have been with the intent of understanding the role of higher harmonics on thermoacoustic refrigeration. After a brief description of experimental apparatus two sets of data will be presented that illustrate the nature of the physics.

The tube is 3.8 meters in overall length and consists of two sections of aluminum pipe with an inner diameter of 2 inches and a wall thickness of 0.5 inches. The driver is commercial shaker unit. The shaker vibrates a piston that reciprocates inside an aluminum sleeve that forms one end of the resonator. The other end of the tube is rigid. Three piston rings made from Rulon, a low friction polymeric material ensure that the motion of the driver is smooth and that the seal is gas tight. The vibrator is driven by a power amplifier that receives its input from a signal generator. The signal generator was set up to produce sine-waves or combinations of sine-waves.

The stack is cut from a ceramic material originally intended to be used to support catalysts. It consists of square parallel ducts with a cell density of 200 per square inch and a porosity of 0.8. A section of this stack was cut to a length of 5.0 cm after being turned so as to fit tightly into the cylindrical resonator. The ducts are aligned parallel to the axis. The stack is located 1/4 of the length of tube away from the driver. Heat exchangers have been built to go with this system but have not yet been used in any of the experiments described in this report.

The amplitude to which the fundamental can be driven is limited by the 0.75 inch maximum peak-to-peak excursion distance of the shaker piston. With the tube full of air at atmospheric pressure this leads to a maximum peak-to-peak pressure swing of 12% in the empty tube and 7% in the presence of the extra damping caused by the stack.

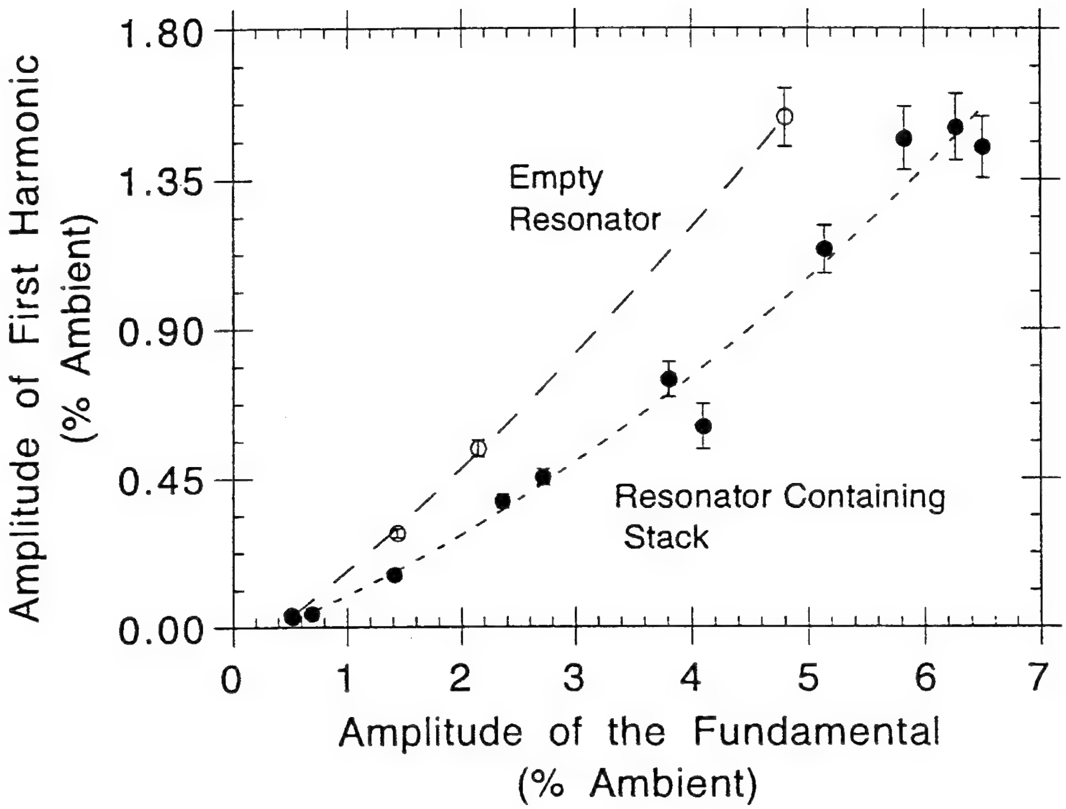
The majority of the research performed to date has been done to determine the effect of the presence of higher harmonics on the refrigerator. In order to simplify the system, experiments have been done using only the stack without the neighboring heat exchangers. Two sets of results are highlighted in this report, first the generation of higher harmonics and then a set of

measurements which demonstrate how the presence of higher harmonics affects the temperature difference across the stack.

The tube was driven at its resonant frequency of 43 Hz over a range of amplitudes. The Fourier transform of the output of both a microphone positioned close to the driver and the accelerometer was taken at each amplitude. The spectrum of the accelerometer reading allows the effect of unavoidable high frequency components in motion of the piston to be quantified. Figure 7 shows the amplitude of the pressure fluctuation measured at twice the natural frequency as a function of the amplitude of the fundamental mode. The length of the error bars corresponds to the pressure amplitude which we predict is produced by the component of the motion of the driver at the frequency of the first harmonic. For a given fundamental amplitude, the presence of the stack decreases the amplitude of the first harmonic by a factor of 0.7. The reduction of the level of the harmonic due to the presence of the stack can be explained by the fact that the reduces the quality of resonance at all frequencies. Whether any of the sound energy that is absorbed by the stack at higher frequencies actually enhances or suppresses the refrigeration is a question that our research hopes to answer.

The linear theory of thermoacoustics predicts that if two frequency components are present in the wave field the heat flow generated will be the sum of the heat flows that each wave would generate if it were alone.[1] Higher harmonics will result in heat transfer which might enhance or reduce that caused by the fundamental. One goal of our research is to check the validity of this assumption at high amplitudes.

Rather than rely on the higher harmonics "naturally" produced by the fundamental we create our own harmonics by driving the piston at two frequencies simultaneously. Thermocouples were glued to the ends of the stack and the equilibrium temperature difference between them measured while driving the tube simultaneously at both the fundamental and twice the fundamental. The amplitude of the fundamental oscillation was kept constant at a moderately high level while the amplitude of the first harmonic was varied over the full range experimentally allowed. The system was driven at each amplitude for a length of time sufficient for the



1.80
1.35
0.90
0.45
0.00
0
1
2
3
4
5
6
7
Amplitude of First Harmonic (% Ambient)
Amplitude of the Fundamental (% Ambient)
Empty Resonator
Resonator Containing Stack

Figure 7

temperature difference between the ends of the stack to reach a steady state. The results are shown in Fig. 8. The horizontal dotted lines represent the temperature differences that each of the two frequency components of the wavefield would generate if it were present by itself. The point to note is that by itself the harmonic is not capable of creating any temperature difference but is capable of reducing the temperature difference created by the fundamental by a factor of a third. This shows clearly that the temperature differences created by the waves are not linearly additive.

Efforts are on going to increase understanding of the relationship between thermoacoustic heat flows and the temperature differences they generate. The most promising method of measuring the heat flow in the stack is to observe the rate of change of temperature when the sound field is first turned on. This will then be applied to the problem of finding out how the heat flows due to different frequency components add.

SUMMARY

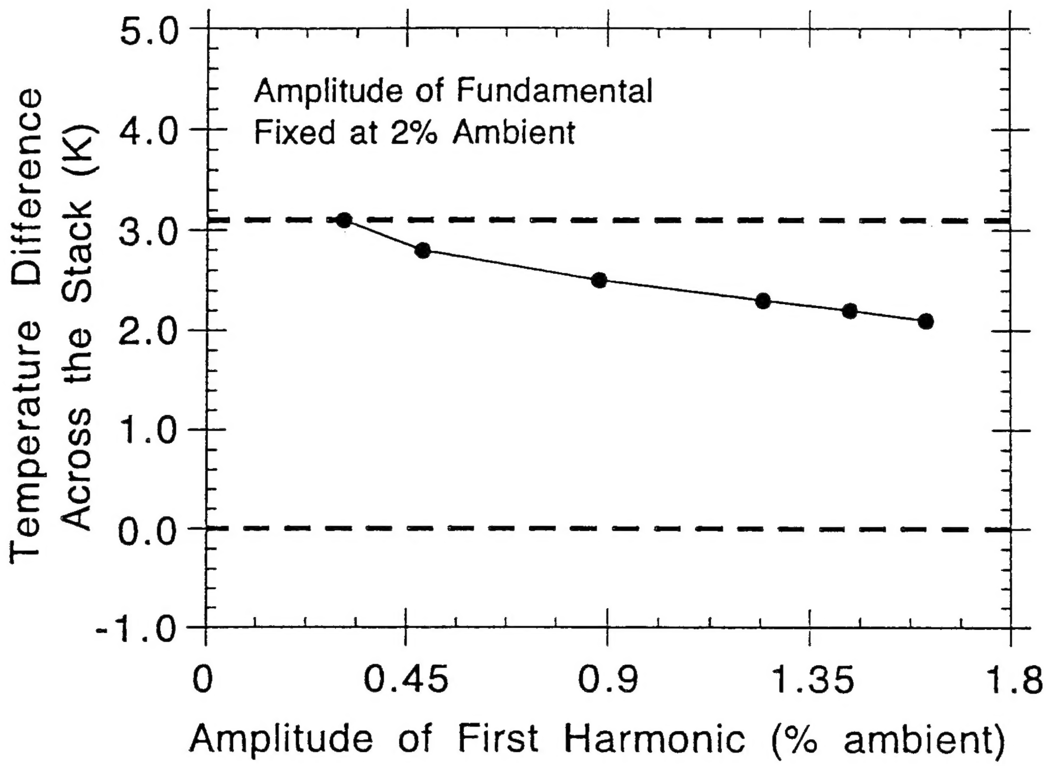
The present research program is funded through September 1995. We expect Mr. Belcher and possibly Mr. Lightfoot to complete their dissertations by then. Mr. Belcher's dissertation deals specifically with element interaction and will include complete experimental results regarding heat exchanger size and placement of elements for a heat driven refrigerator. That much is critical for the next phase we shall propose — a high capacity heat driven refrigerator. Mr. Lightfoot's dissertation will deal with radial engines/refrigerators and variable plate spacing. Dr. Brewster, the postdoc working on this project, will provide continuity until Mr. Webster (a new graduate student) becomes thoroughly familiar with the research project. Dr. Brewster will continue his work on high amplitude effects. We need to identify the important phenomena that limit high amplitude operation and explore methods to circumvent the limitations imposed.

Nearing the end of this three year project, the original goals set out in our proposal are within reach. Our ability to achieve these goals has been as much due to research performed at the Naval Postgraduate School and Los Alamos National Laboratory as by our own work. Tom

Hofler, Anthony Atchley, Steve Garrett, and Greg Swift have contributed freely their thoughts and time. We appreciate their spirit of cooperation.

REFERENCES

1. G.W. Swift, "Analysis and performance of a large thermoacoustic engine," J. Acoust. soc. Am. 92 93), 1151 (1992).



Amplitude of Fundamental
Fixed at 2% Ambient
Temperature Difference
Across the Stack (K)
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
0
0.45
0.9
1.35
1.8
Amplitude of First Harmonic (% ambient)

Figure 8

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Principal Investigator:	Henry E. Bass
Mailing Address:	Physical Acoustics Research Group Dept. of Physics and Astronomy The University of Mississippi University, MS 38677
Phone Number:	601-232-5905
E-Mail Address:	pabass@sparc.ncpa.olemiss.edu

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(list attached)

c. Number of Books or Chapters Submitted but not yet Published:
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d. Number of Books or Chapters Published: 0

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f. Number of Patents Filed: 0

g. Number of Patents Granted: 0

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 0

i. Number of Presentations at Workshops or Prof. Society Meetings:
2

j. Honors/Awards/Prizes for Contract/Grant Employees: 0

k. Total number of Graduate Students and Post-Docs Supported at least 25% this year on this contract/grant:

Grad Students 2 and Post-Docs 1 including

Grad Student Female 0 and Post-Docs Female 0

Grad Student Minority 0 and Post-Doc Minority 0

Minorities include Blacks, Aleuts, Am. Indians, Hispanics, etc. NB: Asians are not considered an under-represented or minority group in science and engineering.

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1 JUNE 1994 through 31 May 1995

ATTACHMENTS

a. Papers Submitted to Refereed Journal

Richard Raspet, Bruce Denardo, H. E. Bass, James Brewster, and John Kordomenos, "Investigation of parametric drive of a longitudinal gas-filled resonance tube," submitted to J. Acoust. Soc. Am., March 1995.

John Kordomenos, Anthony Atchley, Richard Raspet and H. E. Bass, "Experimental study of a thermoacoustic termination of a traveling wave tube," submitted to J. Acoust. Soc. Am., May 1995.

b. Papers Published in Refereed Journals

W. Patrick Arnott, James R. Belcher, Richard Raspet, and Henry E. Bass, "Stability analysis of a helium-filled thermoacoustic engine," J. Acoust. Soc. Am. 96, 370-375 (1994).